Opportunities And Challenges For Indium Phosphide And Related Materials: International Technology Roadmap For Semiconductors Perspective

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Outline

- Roadmap Tutorial
- Trends
- Lessons Learned from Existing Roadmaps
- Compound Semiconductors in the ITRS
  http://public.itrs.net/Files/2003ITRS/Home2003.htm
  http://www.itrs.net/Common/2004Update/2004_04_Wireless.pdf
  IEEE Circuits and Devices, Vol. 20, No. 6, December 2004, pp. 38-51.
- Implications for the IPRM Community
- Conclusions

What is a technology Roadmap?

A technology roadmap in the context of this talk

is an industrial consensus

with inputs from the research community and

if appropriate with inputs from governments.

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Technology Roadmaps

" A *roadmap* is an extended look at the future of a chosen field of inquiry composed from the collective knowledge and imagination of the brightest drivers of change in that field."

----- Robert Galvin, Chairman of the Executive Committee of Motorola, editorial in *Science* 280, 8 May 1998, p. 803.

Why is a technology roadmap useful?

It increases the rates of both technology development and deployment.

A technology roadmap is an effective technique to

1) **Reduce uncertainties in investments**
2) **Use changes among competing technologies as opportunities**
3) **Increase the probability for more robust economic performance**
4) **Guide critical research**
5) **Assist in setting priorities for resource allocations**

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Why You Should Be Interested in Roadmaps?

- Some InP and related compound semiconductors coexist/compete with other III-Vs and with Si and SiGe (i.e., with CMOS compatible processing).

- Smaller budgets place greater emphases on consensus-based planning for smarter investments.

- Participants identify what is common knowledge and what is truly intellectual property.

- Participants gain knowledge, broaden their industrial outlook and awareness, and become more valuable employees.

When is a technology roadmap most effective?

When it:

1) **Increases industrial cooperation and**

2) **Produces positive changes in how companies work together.**

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Trends

- Bigger wafers and smaller devices.
- Increased R & D and production facilities costs are becoming too great for any one company or country.
- Shorter process technology life cycles.
- Emphasis on faster characterization of manufacturing processes.
- All - global participants in the “Si CMOS ecosystem” now collaborate to develop and improve manufacturing technologies; e.g., ITRS and International SEMATECH.

Trends (continued)

- **Competition among Si CMOS manufacturers is shifting from an emphasis on technology and fabrication to a much greater emphasis on product design, architecture, algorithm, and software; i.e., shift from technology-oriented R&D to product-oriented R&D.**

- **Many observers credit consensus-based planning and deliberate roadmapping efforts for the sustained average annual growth rate of 15% for the silicon semiconductor industry over this past decade.**

- **Users interested more in function and price than in process.**

Trends (continued)

- **Communications products may replace computers as a key driver of volume manufacturing.**

- **Present and future volume products include:**
  - **cell phones and video phones**
  - **Bluetooth appliances**
  - **optoelectronics**
  - **automotive electronics that add functionality of home and office to cars and trucks.**

History – Where are compounds addressed?

- **NEMI (2004 Roadmaps)**
  - **some material specificity in energy storage, RF components, and optoelectronics**
  - **numerous market applications**
- **ITRS (2003 Edition and 2004 Update, and 2005 Edition in-progress)**
  - **very material and process specific (limited until 2001 to primarily to crystalline Si CMOS; but now has RF and AMS compounds)**
  - **limited to a few very big market applications (microprocessor-logic, memory, and RF and analog/mixed-signal)**
  - **simple metrics for determining progress (e.g., line width, and density)**
- **OIDA (Recent Reports)**
  - **some material specificity in sensors and detectors**
  - **numerous market applications**

Lessons Learned from Si CMOS Roadmaps

- **Many technology barriers, once thought to be of concern to a few companies, are common through out the industry. Overcoming such barriers offers an appropriate focus for technology roadmaps.**

- **Prior to mid 1980's, most Si CMOS companies assumed that over 50% of what they knew was proprietary and not to be part of consensus-based planning and collaborations.**

- **From the late 1980's to today, most Si CMOS companies found that over 50% of what they know is not proprietary and may be shared with other companies for a globally more competitive industry.**

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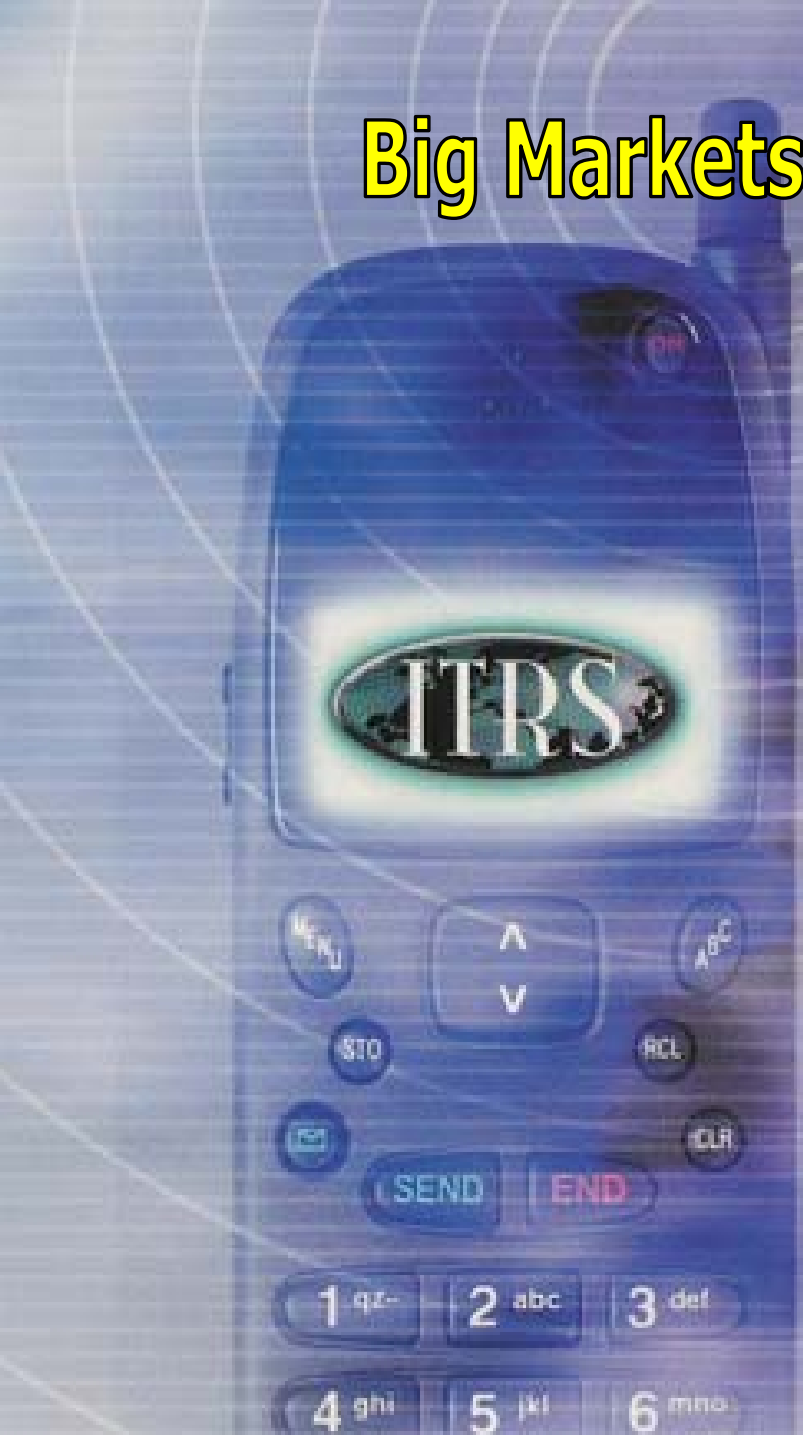
Lessons Learned from NEMI

- Discussions with senior industrial managers for acceptance.
- Worked from a "virtual product" as basis for bringing all stakeholders together.
- Challenge was to have a large enough effort to be effective, but still focussed enough to have measurable progress.
- Everyone has similar problems. Much IP is common to everyone. Industry moves faster when these are recognized and common problems are solved.

Big Markets for Semiconductors



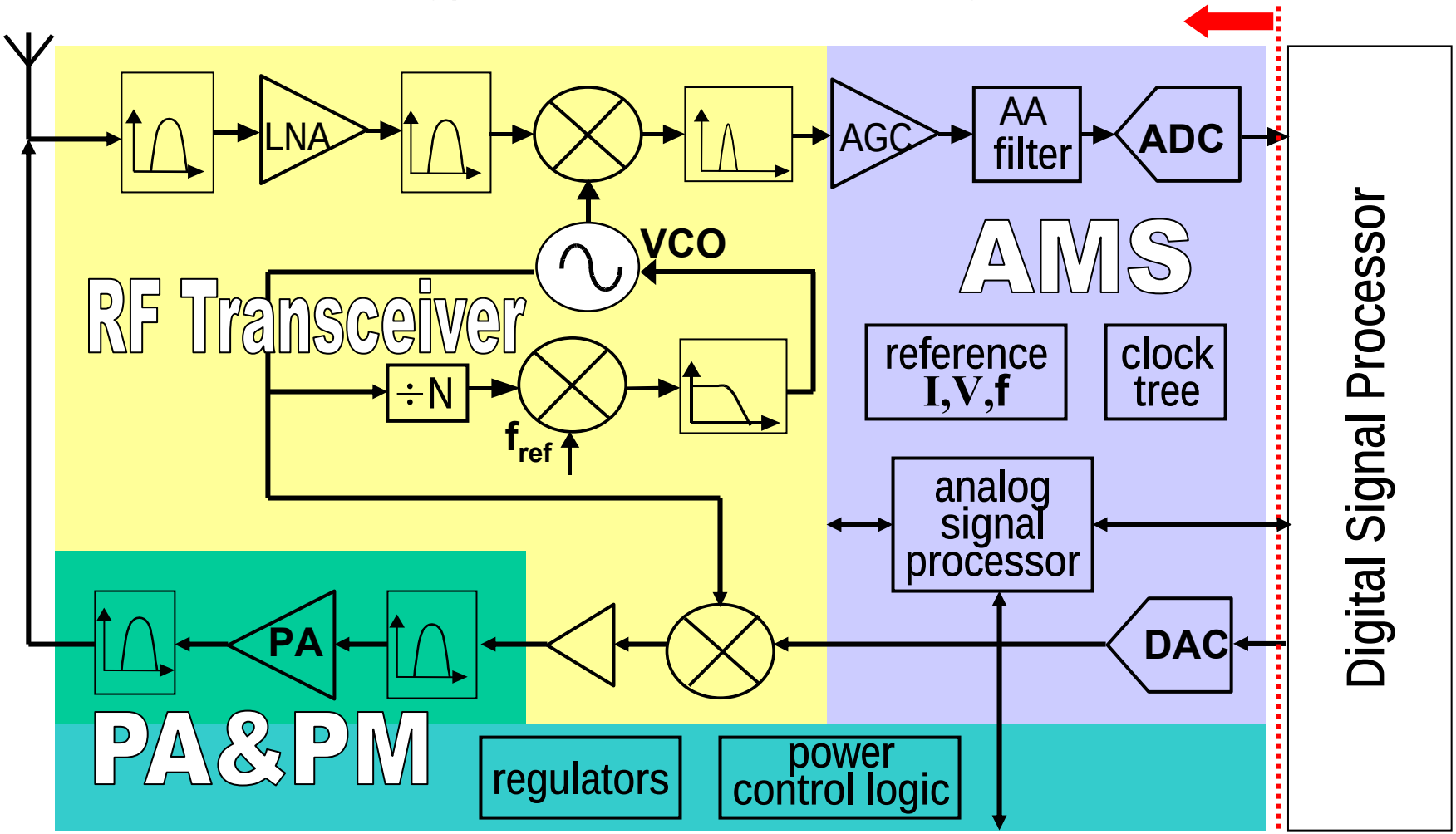
Radio-Frequency and Analog/
Mixed-Signal Circuits and Devices
for Wireless Communications

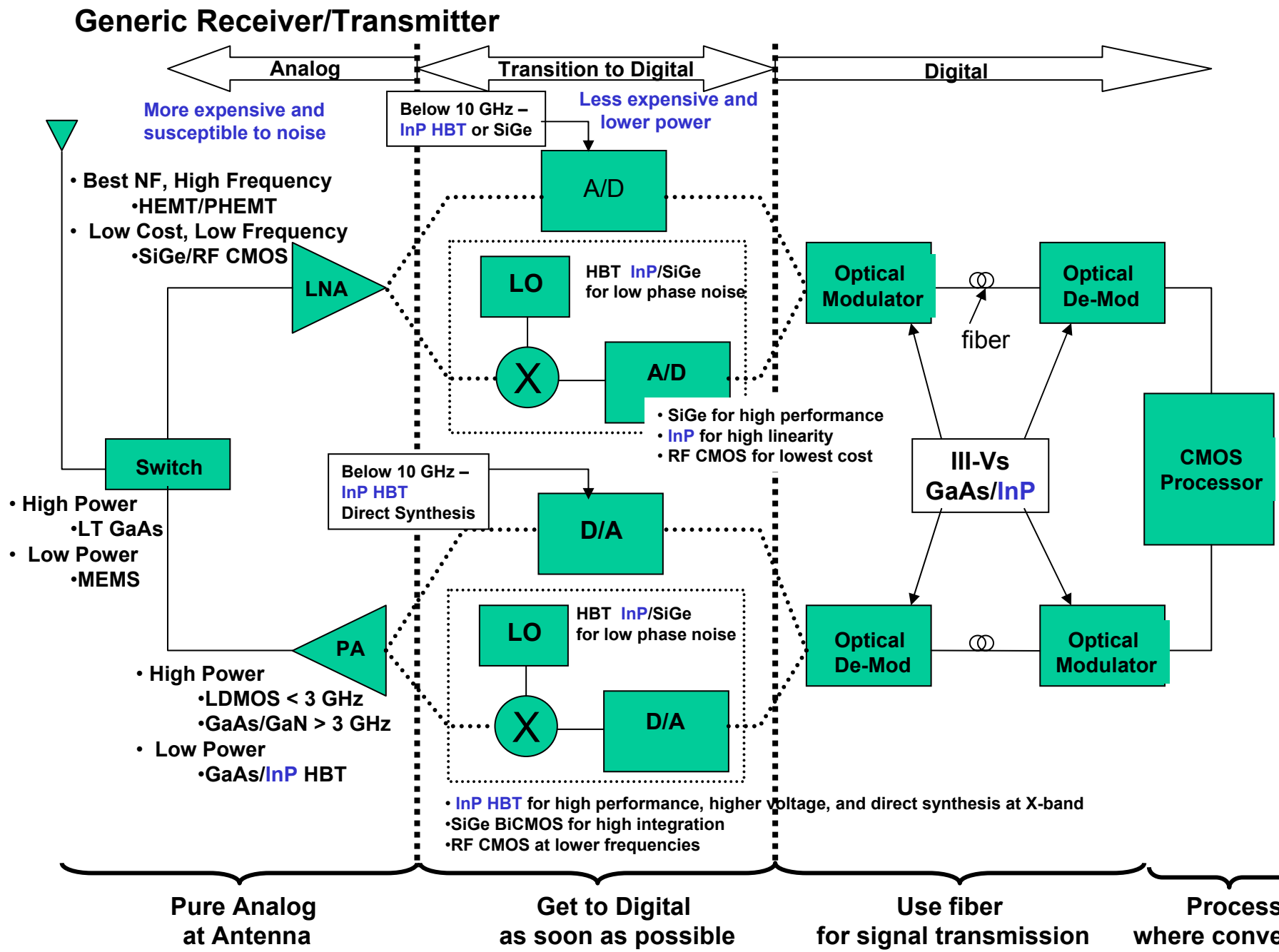
RF and AMS

IEEE Circuits and Devices, Vol. 20, No. 6, December 2004, pp. 38-51.

Scope of RF and AMS Technology Roadmap

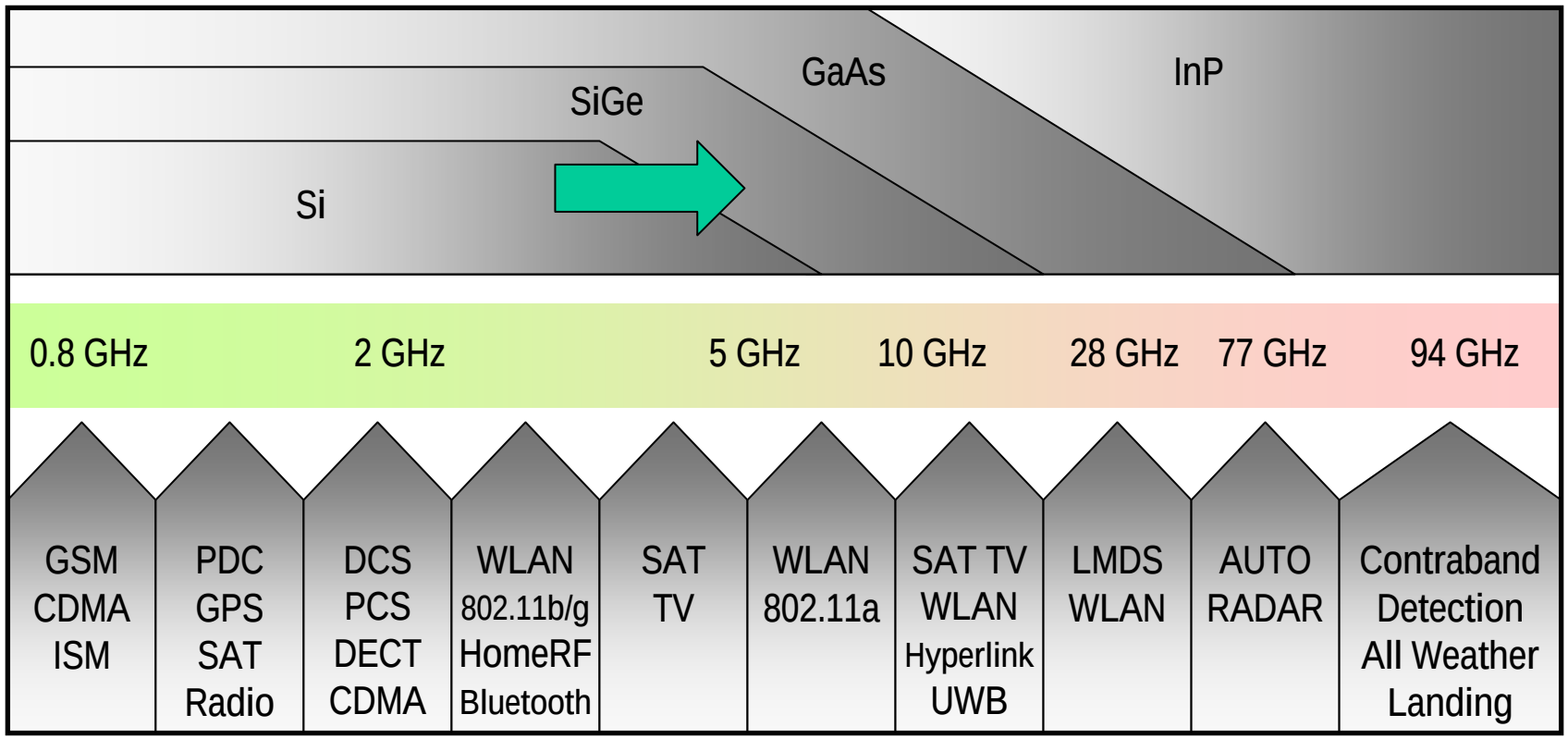
Circuit functions of a typical mobile communication system 0.8 GHz -100GHz




Generic Receiver/Transmitter
Analog
Transition to Digital
Digital
More expensive and susceptible to noise
Below 10 GHz – InP HBT or SiGe
Less expensive and lower power
• Best NF, High Frequency
•HEMT/PHEMT
• Low Cost, Low Frequency
•SiGe/RF CMOS
LNA
A/D
LO
HBT InP/SiGe for low phase noise
X
A/D
• SiGe for high performance
• InP for high linearity
• RF CMOS for lowest cost
Optical Modulator
fiber
Optical De-Mod
Switch
• High Power
•LT GaAs
• Low Power
•MEMS
Below 10 GHz – InP HBT Direct Synthesis
D/A
III-Vs GaAs/InP
CMOS Processor
PA
• High Power
•LDMOS < 3 GHz
•GaAs/GaN > 3 GHz
• Low Power
•GaAs/InP HBT
LO
HBT InP/SiGe for low phase noise
X
D/A
Optical De-Mod
Optical Modulator
• InP HBT for high performance, higher voltage, and direct synthesis at X-band
•SiGe BiCMOS for high integration
•RF CMOS at lower frequencies
Pure Analog at Antenna
Get to Digital as soon as possible
Use fiber for signal transmission
Process where convenient

2005 Application Spectrum

Today's Technology Options for Designers



What will be the technology options in 2011? Will frequency continue to be a technology differentiator or will it be noise, output power, efficiency, linearity, high voltage operation, and cost?

RF and AMS ITWG Objectives

- **Use wireless IC as system / technology driver for ITRS**
- **Address intersection of Si-based technologies with III-V compound semiconductors and other potential technologies (MEMS, BAW, Passives, ..)**
- **Present technical challenges and requirements for AMS & RF IC technologies in wireless applications for cellular phones, WLAN/WPAN, automotive radar, and phased array RF systems, frequencies 0.8 GHz - 100GHz**
- **34 members (22 US, 6 Europe, and 6 Asian Pacific)**
- **Divide RF and AMS Working Group into 5 sub-groups**
  - **CMOS for RF and AMS (0.8 GHz - 10 GHz)**
  - **Bipolar for RF and AMS (0.8 GHz - 10 GHz)**
  - **Power Amplifiers and Power Management (0.8 GHz – 10 GHz)**
  - **Passives for RF&AMS and PA (0.8 GHz – 10 GHz)**
  - **Millimeter Wave (10 GHz – 100 GHz)**

RF and AMS ITWG Objectives

- **Generates roadmap tables in each of the 5 areas:**
  requirements, difficult challenges, potential solutions

- **Tables cover technologies**
  Si CMOS, SiGe HBT, Si LDMOS, GaAs, InP, SiC, GaN
  and device structures
  MOSFET, MESFET, PHEMT, MHEMT, HBT, LDMOS, on-chip passives

- **Outcome: RF & AMS technology roadmap**

Key Considerations

- Drivers for Wireless Communications
  - Cost (die size, part count)
  - Power consumption
  - Functionality
  - Device operating frequencies, channel bandwidth, transmit power, etc. – determined by wireless communication standards and protocols

- Non-traditional ITRS roadmap parameters
  - Regulations from governments determine system spectrum
  - Standards and protocols drive frequencies and performance
  - Production – may be initially specialty foundries and captive
  - applications

- Cost / Performance drives integration
  - Signal Isolation (technology, circuit/system, EDA)
  - Analog shrink (power supply, area, novel device structures)
  - Filters and T/R switches integration (MEMS)
  - Multi-band Multi-mode applications SOC vs. SIP / RF modules

Difficult Challenges for InP and Related Materials

1) Reduction in cost and larger diameter InP wafers to lower the cost per function and per unit area

2) High aspect ratio vias in production processes for dense mm-wave circuits

3) Advances in metamorphic InP technology – buffer layers with lower stresses and improve thermal conductivities

4) Production capability for InP based devices and ICs – diversity in production versus reliable second sources

5) Difficulty and cost of integrating various analog/RF and digital functions on a chip or in a module

Implications for the IPRM Community Selected III-V Difficult Challenges

- **Compound semiconductor substrate quality**
- **Signal isolation – a role for more optoelectronics**
- **Process equipment for fabrication at low cost**
- **Larger size compound substrates [GaAs, SiC and InP] for lower chip costs and compatibility with silicon processing equipment**
- **Epitaxial layers in compound semiconductors - engineering to relieve stress in heteroepitaxy**
- **Increased RF performance for III-Vs predominantly through materials and bandgap enginnering; not through scaling as in silicon technologies**

RF and AMS "Production"

- **ITRS consensus for when Si CMOS "production" based on a new technology begins for ITRS Technology Requirements Tables**
  - **10K wafers per month by one company or foundry followed within 2 or 3 months by another company or foundry – i.e., multiple sources for secure supply, continued innovation and price competition**

- **ITRS consensus for RF and AMS "production" does not exist. RF and AMS companies have many more different business models**
  - **suggestions include:**
    - **a) 5K wafers per year**
    - **b) 2% to 5 % of an existing market – total existing market (TAM)**
    - **c) Insertion into volume products by a captive foundry**

Table 57 Millimeter Wave 10–100 GHz Technology Requirements—Near-term UPDATED (continued) - excerpts from 2004 ITRS UPDATE

Year of Production	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Technology Node		*hp90*			*hp65*		
DRAM ½ Pitch (nm)	*100*	*90*	*80*	*70*	*65*	*57*	*50*
Device Technology—FET							
InP HEMT (low noise)							
Gate length (nm)	-	100	70	70	50	50	32
F_t (GHz)	-	200	240	240	300	300	350
Breakdown (volts)	-	4	3.5	3.5	3	3	2.5
I_{max} (ma/mm)	-	700	700	700	650	650	600
G_m (S/mm)	-	1	1.2	1.2	1.5	1.5	1.8
NF (dB) at 26 GHz, 20–23 dB associated gain							
NF (dB) at 94 GHz, 10–13 dB associated gain							
InP HEMT (power)							
Gate length (nm)							
F_{max} (GHz)							
Breakdown (volts)							
I_{max} (ma/mm)							
G_m (S/mm)	-	-	0.8	0.9	0.9	0.9	0.9
P_{out} at 26 GHz and peak efficiency (mW/mm)	-	-	400	400	450	450	450
Peak efficiency at 26 GHz (%)	-	-	30	40	50	50	50
Gain at 26 GHz, at P_{1dB} (dB)***	-	-	12	15	15	16	16
P_{out} at 94 GHz and peak efficiency (mW/mm)	-	-	250	300	350	350	400
Peak efficiency at 94 GHz (%)	-	-	25	40	40	45	45
Gain at 94 GHz, at P_{1dB} (dB)***	-	-	6	8	10	10	12

Although the gap between InP and SiGe is closing, InP has the advantage of higher breakdown voltages while SiGe BiCMOS has the advantage of higher integration densities.

Table 57 Millimeter Wave 10–100 GHz Technology Requirements—Near-term UPDATED (continued) - excerpts from 2004 ITRS UPDATE

Year of Production	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Technology Node		*hp90*			*hp65*		
DRAM ½ Pitch (nm)	*100*	*90*	*80*	*70*	*65*	*57*	*50*
Device Technology—FET							
GaAs MHEMT (low noise)							
Gate length (nm)							
F_t (GHz)							
Breakdown (volts)							
I_{max} (ma/mm)							
G_m (S/mm)							
NF (dB) at 26 GHz, 10–23 dB associate							
NF (dB) at 94 GHz, 10–13 dB associate							
GaAs MHEMT (Power)							
Gate length (nm)							
F_{max} (GHz)	-	-	-	200	250	275	300
Breakdown (volts)	-	-	-	8	8	8	9
I_{max} (ma/mm)	-	-	-	600	600	600	600
G_m (S/mm)	-	-	-	0.8	0.9	0.9	0.9
P_{out} at 26 GHz and peak efficiency (mW/mm)	-	-	-	350	500	600	750
Peak efficiency at 26 GHz (%)	-	-	-	45	55	55	60
Gain at 26 GHz, at P_{1dB} (dB)***	-	-	-	12	15	16	16
P_{out} at 94 GHz and peak efficiency (mW/mm)	-	-	-	200	350	400	450
Peak efficiency at 94 GHz (%)	-	-	-	25	40	45	45
Gain at 94 GHz, at P_{1dB} (dB)***	-	-	-	6	8	10	12

GaAs MHEMT will supplant GaAs PHEMTs and InP HEMTs for low noise front end and power applications above 40 GHz.

III-Vs enable higher operating voltages than either SiGe or CMOS and greater RF power densities for base stations.

Table 57 Millimeter Wave 10–100 GHz Technology Requirements—Near-term UPDATED (continued) - excerpts from 2004 ITRS UPDATE

Year of Production	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Technology Node		*hp90*			*hp65*		
DRAM ½ Pitch (nm)	*100*	*90*	*80*	*70*	*65*	*57*	*50*
Device Technology—HBT							
InP HBT							
Emitter width (nm)	**1200**	**800**	**350**	**350**	**250**	**250**	**150**
F_t (GHz)	**170**	**170**	**300**	**300**	**350**	**350**	**400**
F_{max} (GHz)	**170**	**200**	**300**	**300**	**400**	**400**	**450**
Breakdown (BV_{CEO}) (volts)							
$I_{max}/\mu m^2$ (mA/μm^2)							
Beta							
3 sigma V_{BE} (mV)							
Interconnect metal layers							
Interconnect metal							
Interconnect metal							
Barrier	**PVD**	**PVD**	**PVD**	**PVD**	**IMP**	**IMP**	**IMP**
Wafer diameter (mm)	**100**	**100**	**100**	**100**	**150**	**150**	**150**

When efficiency and linearity are critical, InP and GaAs HBTs are best for low power applications.

InP will predominate in the near term for mixed signal applications up to 100 GHz.

Table 57 Millimeter Wave 10–100 GHz Technology Requirements—Near-term UPDATED (continued) - excerpts from 2004 ITRS UPDATE

Year of Production	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Technology Node		*hp90*			*hp65*		
DRAM ½ Pitch (nm)	*100*	*90*	*80*	*70*	*65*	*57*	*50*
Device Technology—HBT							
SiGe HBT							
Emitter Width							
F_t (GHz)							
F_{max} (GHz)							
Breakdown (B							
Breakdown (BV_{CEO}) (volts)	**2.3**	**2**	**2**	**2**	**1.8**	**1.8**	**1.8**
$I_{max}/\mu m^2$ ($mA/\mu m^2$)	**7**	**8**	**10**	**14**	**14**	**18**	**18**
Beta	**140**	**200**	**200**	**200**	**250**	**250**	**300**
Nf_{min} at 77 GHz (dB)	**6.6**	**6.1**	**5.5**	**5.1**	**4.6**	**4.3**	**3.9**

SiGe HBTs challenge InP HBTs for applications up to 40 GHz and will challenge InP HBTs for high volume applications such as auto radar.

Lessons from RF and AMS Roadmap

More inputs from the physics, chemistry, and metrology communities

- Understand electrical contacts well enough to control and reproduce in high volumes their RF and AMS properties

- Alternative isolation methods based on optoelectronics

- Improve RF and AMS metrology for 1/f noise, PAE, linearity, bandwidth, gain, reliability, and the like.

- Exploit additional degrees of freedom offered by emerging research devices (RTDs, spin transistors, CNTs, molecular electronics, planar double gate transistors, 3D structures including vertical transistors
  - e.g.,
    a) control independently the voltage on multiple-gated devices
    b) apply electric field perpendicular to the axis of CNT to alter the band structure

3G Spans IEEE Technical Interests

BY ERICA VONDERHEID
Assistant Editor,
THE INSTITUTE

Third generation wireless (3G) technology promises users more bandwidth, security and reliability. Circuits, antennas, power supply, handheld devices, software and more are employed to develop 3G wireless technology. 3G allows up to 2.05 megabits of data a second to be transferred for stationary applications, 384 Kbits while walking and 128 Kbits for users in moving vehicles.

Spanning several technologies

Because 3G spans many technologies, several IEEE Societies have worked together to spread technical information to other researchers and engineers in the field. These include Antennas and Propagation (A&P), Circuits and Systems (CAS), Communications (ComSoc), Computer (CS), Consumer Electronics (CES), Electron Devices (EDS), Lasers and Electro-Optics, Microwave Theory and Techniques (MTT), Power Electronics Society (PELS), Signal Processing Society (SPS), Solid-State Circuits (SSC) and Vehicular Technology (VTS).

"One can argue that all these (3G wireless) applications fall within the scope of the society," said Stuart Lipoff, a past president of IEEE CES.

Members attend different IEEE meetings and conferences or belong to more than one IEEE society, which leads to collaborative efforts. For example, Lipoff said IEEE CES has worked with IEEE VTS and ComSoc. Lipoff is also a former IEEE VTS Conference Chair.

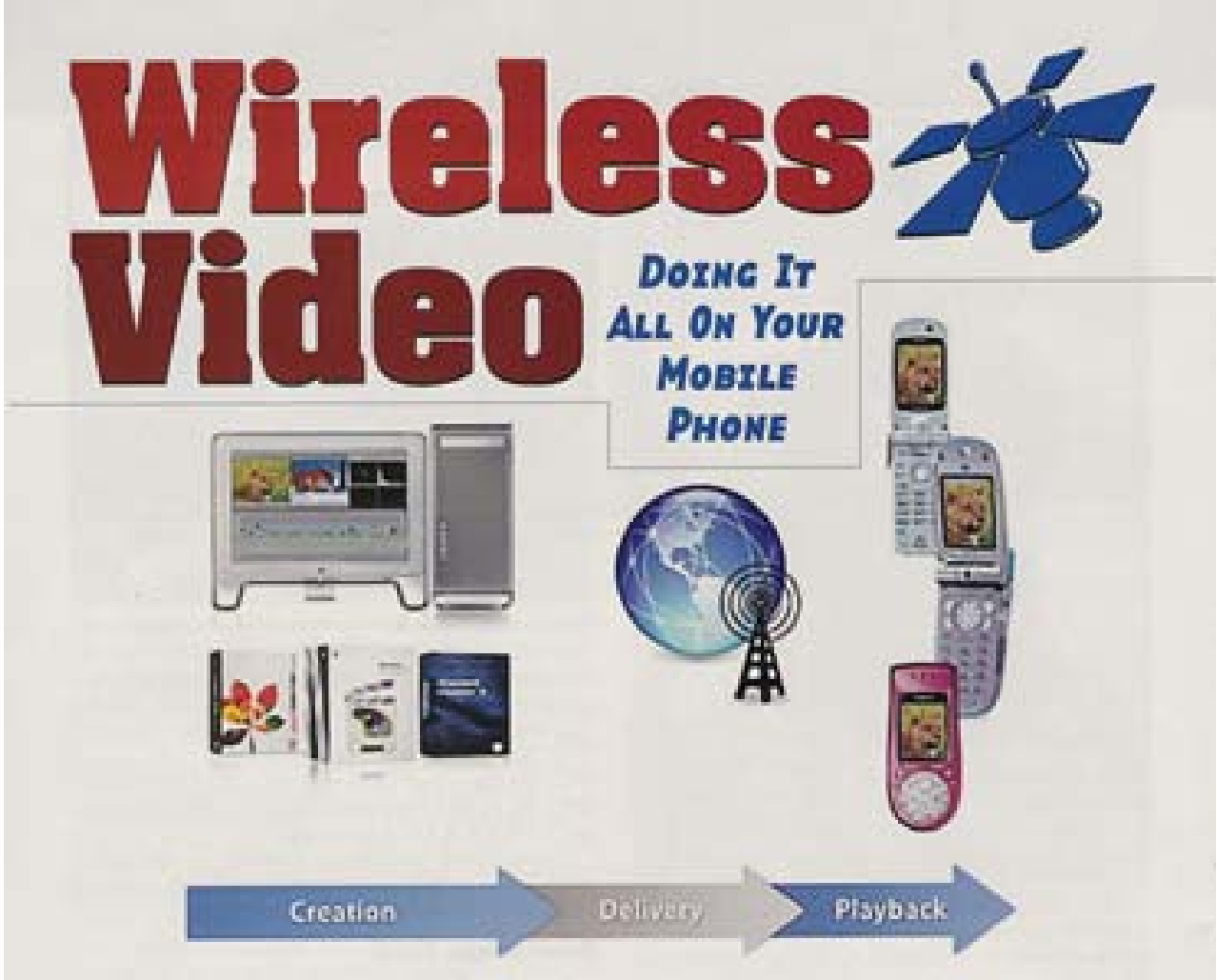
Often, two or more technical societies and councils will co-sponsor a conference or symposium on a topic. Some examples include

- EDS, MTT – 2001 IEEE Sarnoff Symposium: Advances in Wired and Wireless Communications
- VTS, ComSoc – World Wireless Congress in May in San Francisco
- SSC, EDS – 2002 Custom Integrated Circuits Conference, also in May
- CAS, ComSoc, IEEE Neural Networks Council – IEEE International Conference on Circuits and Systems for Communication this May.

IEEE magazines and journals also play a role in publicizing new wireless technology. Among these are – *IEEE Pervasive Computing, IEEE Transactions on Mobile Computing,* [Continued on page 9]

Adapted from The Institute, March 2002, Vol. 26, No. 3, page 1.

Today, 3G – 2 Mbps stationary to 128 Kbps in moving cars, 15 fps, 176x122.
When will nG support HDTV, ~ 100 Mbps, 60 fps, progressive, 1280x720?
What will be the mix of semiconductor materials for nG?



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When will nG support HDTV, ~ 100 Mbps, 60 fps, progressive, 1280x720?
What will be the mix of semiconductor materials for nG?

Adapted from D. Dixon, Camcorder & Computer Video, Magazine, May 2005,Vol. 21, No.5, pp. 68 - 73.

Analog-to-Digital Converter Technology

Needed today for all-digital receivers but will not be available for 22 years at the current rate of evolution – a red brick wall .

Drivers in Handset Application:

- IF Frequency

⇒ Sample Rate

- Dynamic Range

⇒ Resolution

A "Moore's Law" for ADC Technology

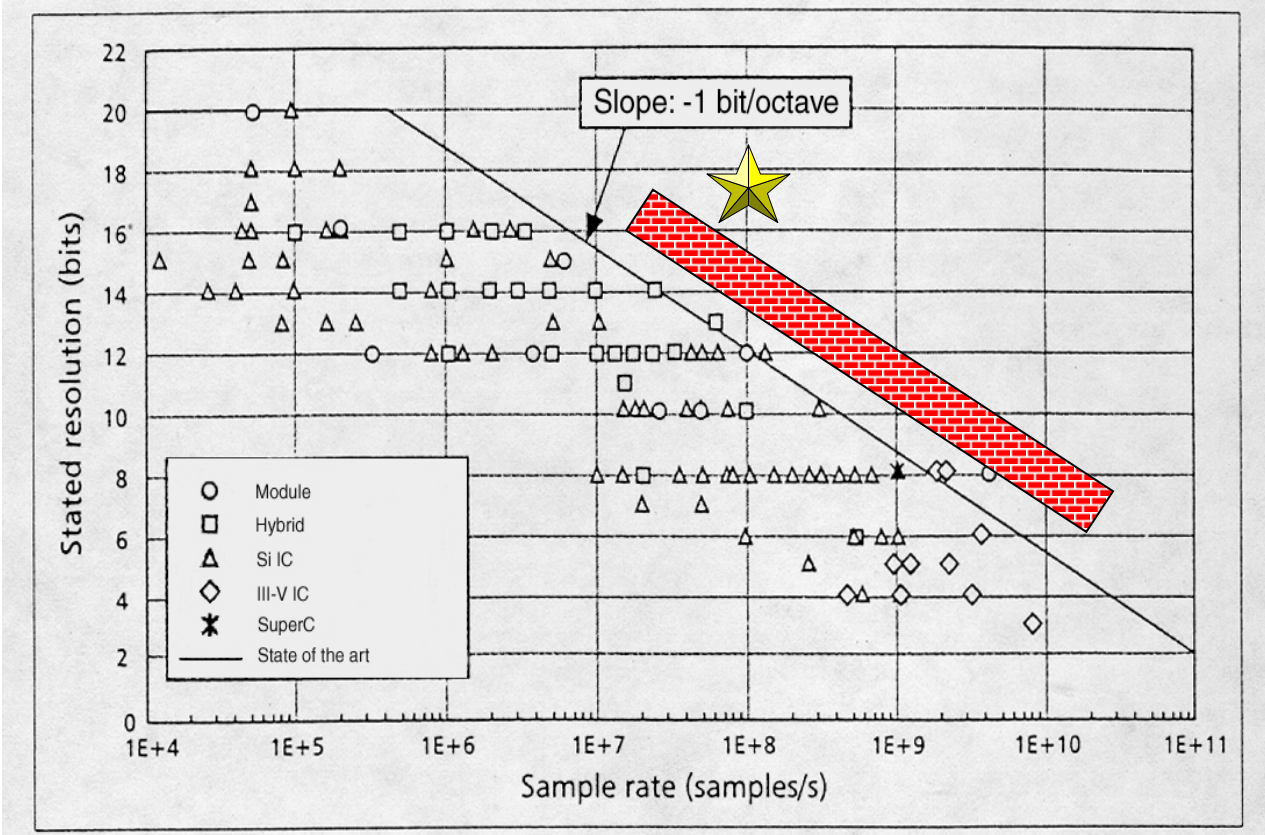


Figure 1. *A survey of analog-to-digital converters.*

Adapted from R. H. Walden, *Performance Trends for Analog-to-Digital Converters*, IEEE Communications Magazine, February 1999, pp. 96 - 101.

CHALLENGES FOR OPTICAL INTERCONNECTS

CMOS industry wants to know when lasers could be co-integrated with CMOS, ITRS 2001 Meeting, 18 July 2001, San Francisco.

Perhaps a strong candidate for inclusion in the 200? ITRS to the same level of detail as RF and AMS Technologies were for the 2003 ITRS

From July 2001 ITRS Public Meeting, there is a need for

- **Viable low-cost manufacturing of**
- **Chip-compatible, high-precision 3D micro(nano)-optical pathways that**
- **Integrate all microelectronics and optoelectronics components to**
- **Interface/interconnect these optoelectronic/microelectronic transceivers**

CHALLENGES FOR OPTICAL INTERCONNECTS
(continued)

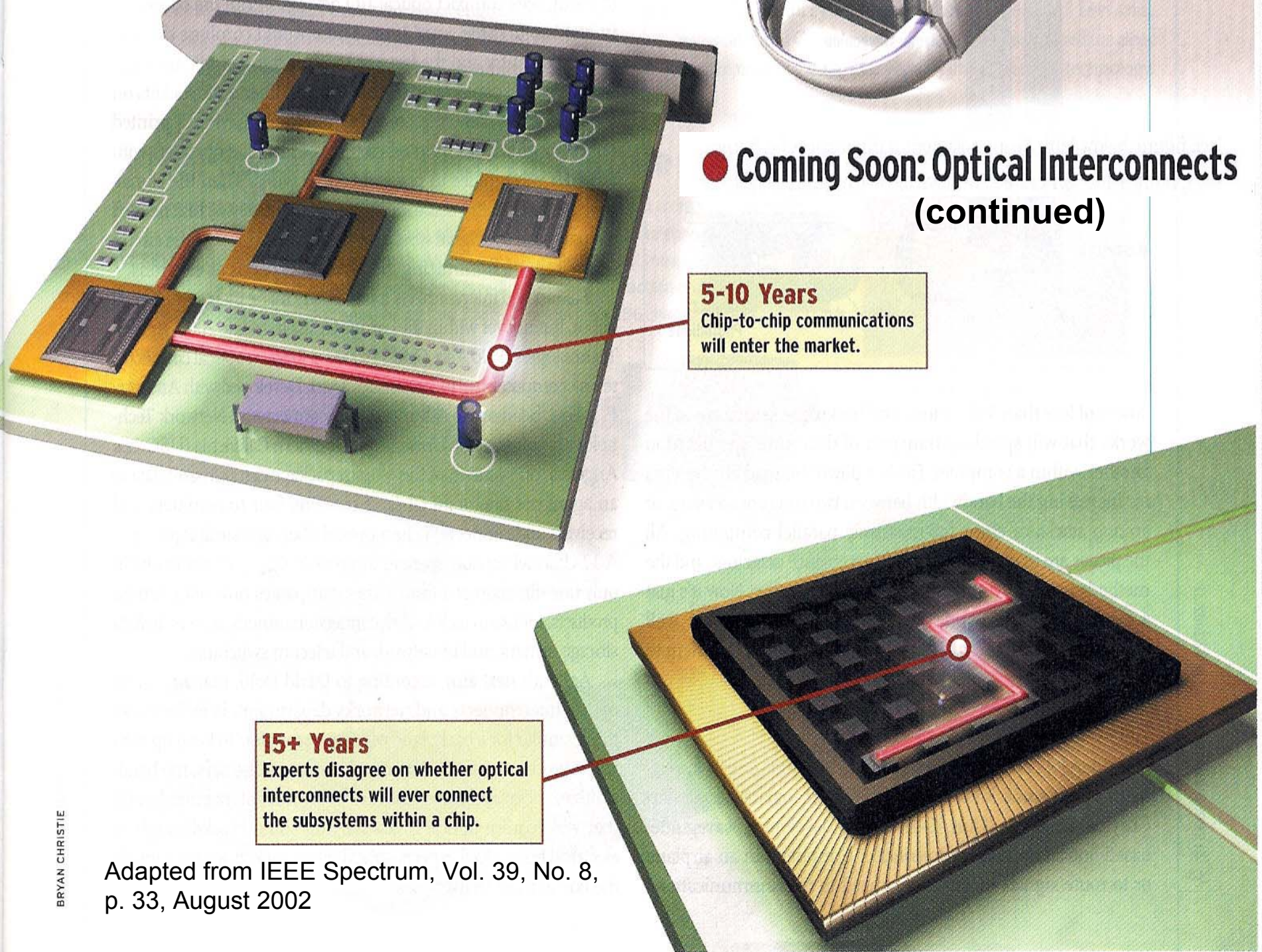
- **Make optoelectronics mainstream for such high volume applications as backplanes in PCs (short term), chip-to-chip (mid term), and perhaps, intra-chip within 15+ years.**

- **CD or DVD transceivers cost about $1.00 but telecom transceivers cost from about $25 for a short-run indoor 1 Gb/s transceiver to over $10,000 for a long-haul 10 Gb/s transceiver card in a network backbone.**

Coming Soon: Optical Interconnects

This approach to signal transfer is moving from longer-distance applications, such as linking separate computers, to joining chips within a computer.

Adapted from IEEE Spectrum, Vol. 39, No. 8, p. 33, August 2002



Adapted from IEEE Spectrum, Vol. 39, No. 8, p. 33, August 2002

CONCLUSIONS

- **International consensus-based planning offers a way to determine priorities in investing funds to support additional R & D and to remove technology gaps between what is available and what the markets require.**

- **In order to deliver its full potential, the compound semiconductor industry needs improved industry, university, and government collaborations.**

RF and AMS

QUOTATION ON TECHNOLOGY ROADMAPS

"No one is big enough to drive the totality of the infrastructure and pre-competitive investments on their own."

----- Avtar Oberai, formerly from IBM and a founding director of SEMATECH, in *Compound Semiconductor* **5**, 44 (April 1999).

RF and AMS

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QUOTATION ON TECHNOLOGY CHOICES

"Never seriously try to make it out of anything else if it has a chance of working with Si" (Woodall's Rule -1982)

"Si-Ge is not Si" (Woodall's Corollary - 1990)

"However, from a "manufacturability" vantage, faster materials may be more cost effective than nanoscale lithography in Si technology as we approach terahertz bandwidth applications or below the current 20-30 nm limits for Si."

----- Jerry M. Woodall, Purdue University, formerly Yale University, at 2004 CS MANTECH.